Combined measurement of LIF and ILIDS for vapor concentration and droplets size and velocity in a spray

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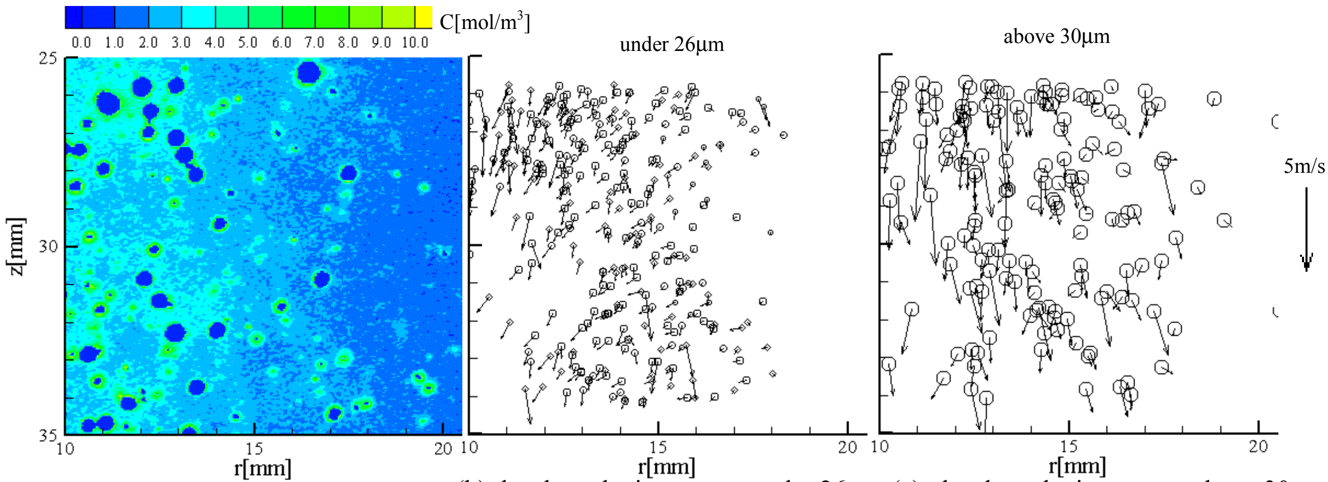
Key Words; *spray, LIF, ILIDS, vapor concentration, droplet sizing*

Abstract

This paper describes the simultaneous measurement of vapor concentration and droplet size distribution in a spray. In the field of spray analysis, various kinds of measurement techniques have been proposed. LIF gives quantitative vapor concentration distribution from raw LIF image by the calibration technique employed in the previous research (Fujikawa *et al.* 1999). Interferometic Laser Imaging for Droplet Sizing (ILIDS) provides instantaneous spatial distributions of droplet size and velocity (Maeda *et al*, 2000, S.M.Skippon *et al*, 1998). Our objective is to accomplish a simultaneous measurement of vapor concentration distribution around droplets, droplet properties (size and velocity) by combining both techniques. We employed acetone as a fluorescence marker and Nd:YAG laser as the excitator for LIF and illumination light source for ILIDS simultaneously. The special optical arrangement of Nd:YAG laser enables us to emit two wavelengths laser beam of 532nm for ILIDS and 266nm for LIF simultaneously. The acetone absorbs the excitation wavelength of 266nm, emits fluorescence of spectrum peak around 435nm, and the droplets scatter incident light of 532nm. As the wavelength of fluorescence differs from the scattered light of 532nm, the use of optical filters enables us to distinguish fluorescence from scattered light from droplets. The experimental result shown in Fig.1 (a) is an instantaneous image at radial position r =15, axial position under the nozzle z = 30, and Fig. 1(b) and (c) show droplet velocity vectors separated by the size (b) under 26μm, (c) above 30μ, and about 100 ILIDS images are merged. We can confirm the periphery of a spray around r=16 and the open circular spots where the strong fluorescence by liquid acetone exists and cut off by an appropriate threshold level. Figure 1 (b) and (c) clearly show the relevancy that bigger droplets flow to the outside of a spray, and the smaller droplets flow to the inside with smaller velocity. The present proposed method could provide the mutual spatial information on distribution of vapor concentration and droplet size and velocity. Further investigation leads to obtaining the precise correspondence of individual size and surrounding atmosphere concentration of particles.



(a);Instantaneous vapor distribution (b);droplet velocity vectors under 26μm (c); droplet velocity vectors above 30μm

Figure 1. Instantaneous vapor concentration distribution and droplet velocity vectors separated by the droplet size (about 100 ILIDS images merged) in a spray at r=15, z=30

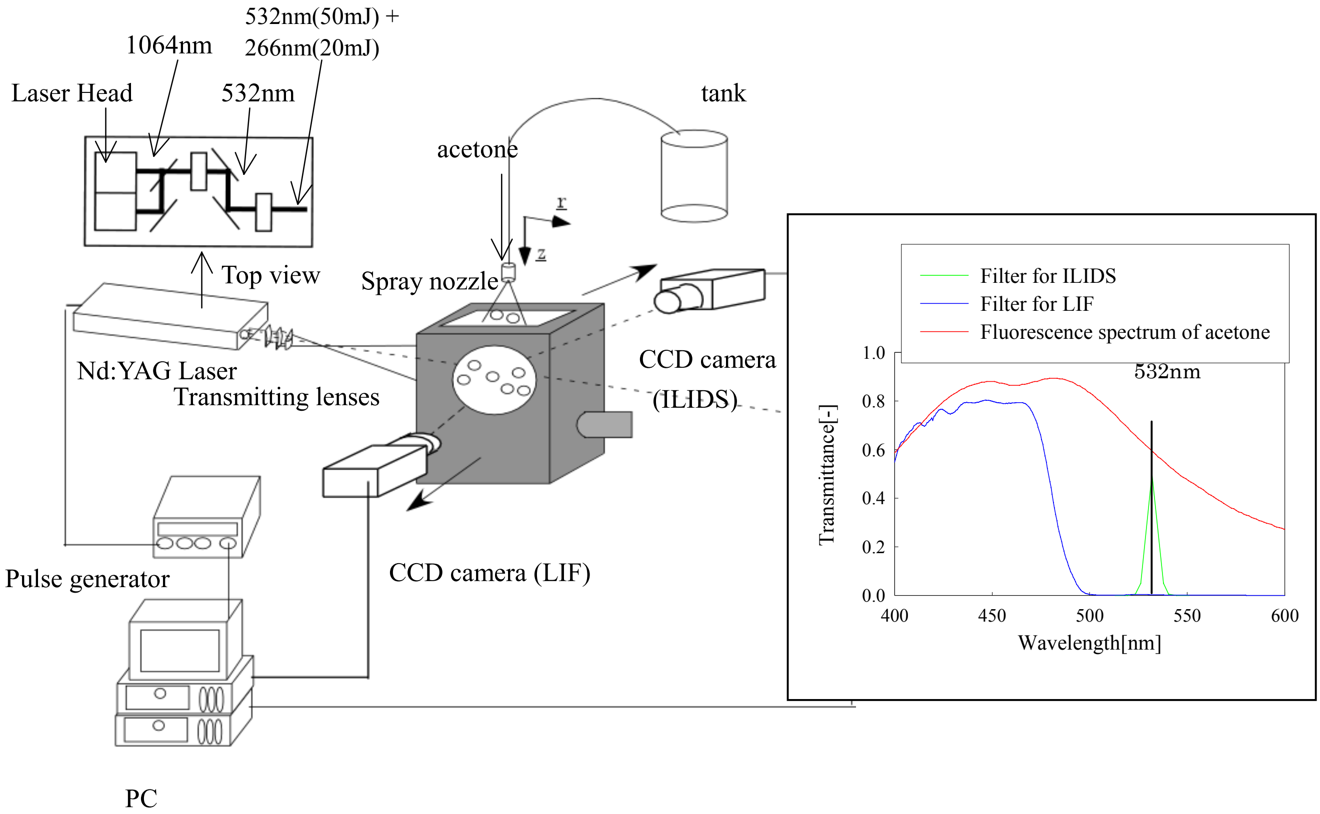
1. Introduction

Detailed studies of spray structures are strongly required advancing the thermal efficiency, and reducing emission from internal combustion engines operating on diffusion controlled spray combustion. Especially, the thorough analysis of the droplets' properties (diameter, velocity), the evaporation of the injected fuel and the mixing with the ambient gas in a spray are expected to contribute these purposes. In the field of spray analysis, various kinds of measurement techniques have been proposed. The Exciplex Fluorescence method, which can measure liquid phase and vapor phase simultaneously, is a powerful tool to a spray (Rotunno *et al*, 1990). The main characteristic of this method lies in the mixture of two fluorescence markers that make the difference of the fluorescence spectrum of vapor and liquid phase. The difference of fluorescence spectrum enables discrimination of vapor and liquid phase and to measure each phase separately and simultaneously. However, it is necessary to use complex calibration for the quantitative measurement that is caused by mixed two fluorescence markers and this is hardly applied under the existence of oxygen that quenches fluorescence. While Fujikawa *et al.* (1999) developed convectional Laser Induced Fluorescence (LIF) with a new compensation method that made it possible to obtain quantitative vapor concentration distribution from raw LIF image. For the measurement of droplet size and velocity, phase-Doppler anemometry (PDA), which gives the size and velocity of individual spherical particles simultaneously, has been improved and well adapted for various applications (Higuchi *et al*, 1994). While PDA is a point measurement, the Interferometric Laser Imaging for Droplet Sizing (ILIDS) is a two-dimensional measurement technique, provides the instantaneous spatial distribution of droplets (Hesselbacher *et al*, 1991, Glover *et al*, 1995). Maeda *et al.* (2000) improved convectional ILIDS applicable to the denser part of a spray with the optics compressing the circular image with fringe vertically, and measured each droplet size and velocity.

The present study attempts to examine the ability of combination with ILIDS for droplets properties (diameter and velocity) and LIF for vapor concentration. Each measurement system requires light source to excite the fluorescence marker and illuminate the droplets in a spray, so we employ Nd:YAG laser and set special optical arrangement to emit two-wavelength laser beam simultaneously. Further, by adopting optical filters to distinguish fluorescence from reflection and refraction, we accomplish simultaneous measurement of vapor concentration distribution and droplet size and velocity. The proposed method provides the mutual spatial relationship between vapor concentration distribution and droplet spacing, diameter and velocity vector so that this measurement system can make good contribute to thorough analysis of sprays.

2. Fundamental apparatus for combined measurement

The experimental setup for combined measurement is shown in Fig.2. The main characteristic of the present method lies in the choice of the laser and the fluorescence marker. Each measurement system requires the light source to excite or illuminate a spray. Moreover, the wavelengths of fluorescence for LIF must be discrete from the scattered light for the ILIDS. We employed Nd:YAG laser with the special optical arrangement to emit the laser beam including two wavelengths (532nm, 266nm) for each measurement and acetone as a fluorescence marker. Acetone absorbs the laser power of 266nm, emit the fluorescence which has the spectrum peak around 435nm, and droplets scatter the light of 532nm without absorbing. The wavelengths of fluorescence and scattered light are discrete each other, so the lights from a spray can be split by the appropriate optical filters. The camera for LIF can capture only fluorescence from acetone, on the other hand, the camera for ILIDS can capture only scattered light. Figure 2 (b) shows the transmission of the optical filters employed in the present study and fluorescence spectrum of acetone (A.Lozano *et al*, 1992). These optical filters distinguish fluorescence from reflection and refraction. These experimental apparatus of the laser with special optical arrangement, acetone as a fluorescence marker, and the optical filters enables us to combine two measurement methods.



(a) Schematic of experimental setup (b) Optical filters and fluorescence spectrum of acetone

Figure.2 Experimental setup

3. LIF technique

3.1 Calibration of LIF

LIF requires an appropriate tracer that emits fluoresces and light source to excite the tracer. We adopted pure acetone as a fluorescence marker and the fourth higher harmonic wavelength Nd:YAG laser (266nm) to excite the acetone. Acetone has the ideal features of its low dependence on pressure and temperature and its optical characteristics. (A.Lozano *et al,* 1992). This choice of fluorescence marker gives us the adaptability to various conditions and helps to avoid the complex correction. Furthermore, acetone doesn't absorb the laser beam of 532nm, there is no influence on the LIF measurement with the laser sheet including 532nm. On the measurement of LIF, we should take it into consideration that the laser sheet itself includes intensity non-uniformity affecting the LIF image. Besides this, the LIF image requires an appropriate calibration to quantify vapor concentration distribution. In the present study, we adopted the compensation method shown in Eq. (1), which was proposed by Fujikawa *et al* (1999)

$$C = C_{ref} \frac{[LIF]-[Back]}{[LIF_{ref}]-[Back]} \tag{1}$$

Where C is vapor concentration [mol/m^3], [LIF] is fluorescence intensity in LIF image, [*Back*] is a background image, C_{ref} is reference concentration [mol/m^3]. The background image was obtained without fluorescence, CCD noise is reduced by subtracting [*Back*] from [*LIF*] and [LIF_{ref}]. The reference image was obtained in an uniform concentration distribution field in a closed chamber and a fluorescence intensity corresponds to the absolute concentration C_{ref} . On the measurement of C_{ref}, the gas in an uniform vapor concentration field is sampled by the syringe and analyzed by gas chromatography. The only one reference image is required to this method on the condition that the laser and the receiving optics are settled to keep the same distribution of non-uniformity.

[LIF_{ref}] and C_{ref} has the very important information of the intensity non-uniformity in the laser sheet and the proportionally factor of fluorescence intensity and absolute concentration by a pixel. Equation (1) can compensate for the intensity non-uniformity in the laser sheet, quantify vapor concentration. This method can work on the assumption that the absolute concentration and LIF intensity are in linear relation, and this relation was confirmed as is shown in Fig.3

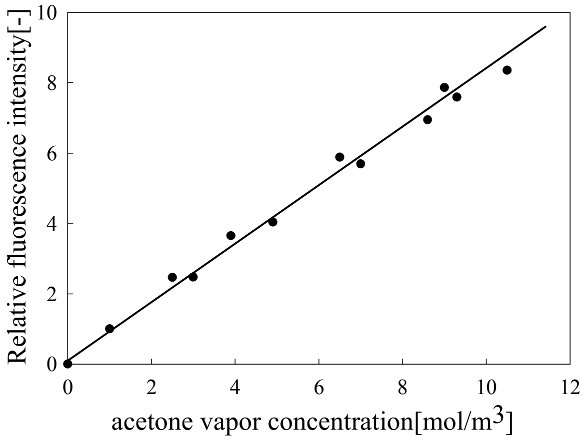
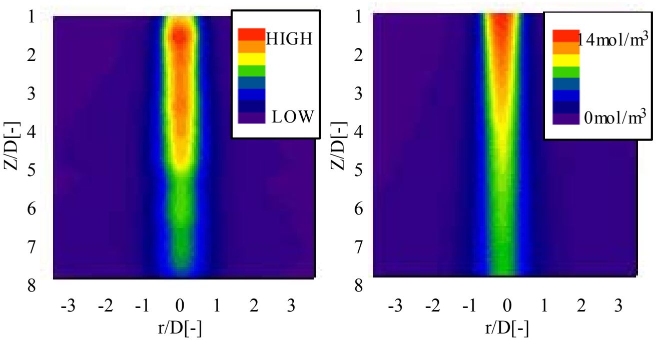


Figure 3. The linearity of fluorescence intensity and acetone vapor concentration

3.1.2 Evaluation the compensation in single phase (acetone vapor) flow

The evaluation of the compensation was carried out in an acetone vapor jet. The experimental conditions were Re = 124, where jet diameter D was 3mm and reference of concentration C_{ref} was 3.0mol/m^3. Figure 4 shows the concentration distribution with and without compensation with the average of 200 images. The figure also shows the effect of the compensation to eliminate the influences of intensity non-uniformity in the laser sheet and quantification of vapor concentration. Figure 5 shows the corresponding normalized concentration distributions of Fig.4 (b); the vertical axis is normalized by C_{max} and the horizontal axis is normalized by L_{hf} that is the r value where concentration is half of C_{max}. We can confirm these lines are in good agreement each other. The accuracy of this method is estimated 6.1% including laser power fluctuation.



(a) without compensation (b) with compensation

Figure4 Concentration distribution (D=3mm, Re=124)

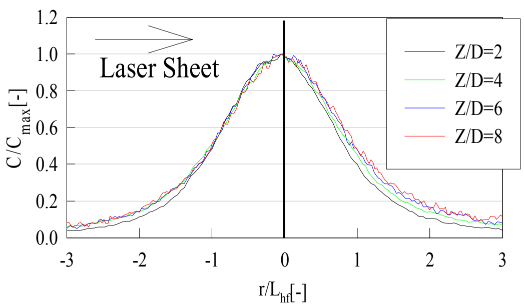


Figure.5 Normalized concentration distributions (D=3mm, Re=124)

3.1.3 Distinction of vapor and droplet

The LIF image shows not only fluorescence from vapor and droplets but also halation coming from the strong fluorescence of droplets illustrated in Fig.6. There is a significant difference in the fluorescence intensity of vapor phase, liquid phase and halation, thus, an appropriate threshold enables us to discriminate vapor phase and droplets, halation and to measure vapor only (R.Bazile *et al*, 1995). Figure 7 shows vapor concentration distribution after cut off by the threshold and the radial vapor concentration profile at indicated line. This profile shows that droplets and halation are clearly cut off and only the vapor is measured. In the present study, we set the threshold acetone's saturated vapor concentration of 10.1mol/m^3 at 293K.

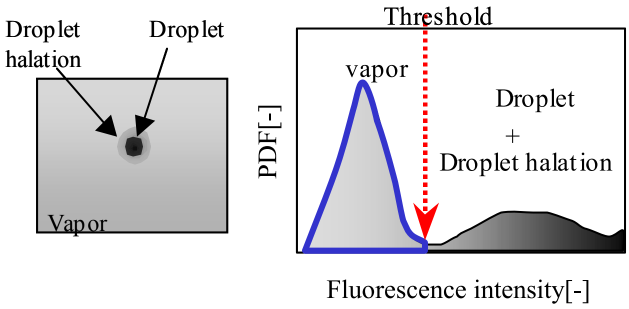


Figure 6 The fluorescence around the droplet and the PDF of fluorescence intensity

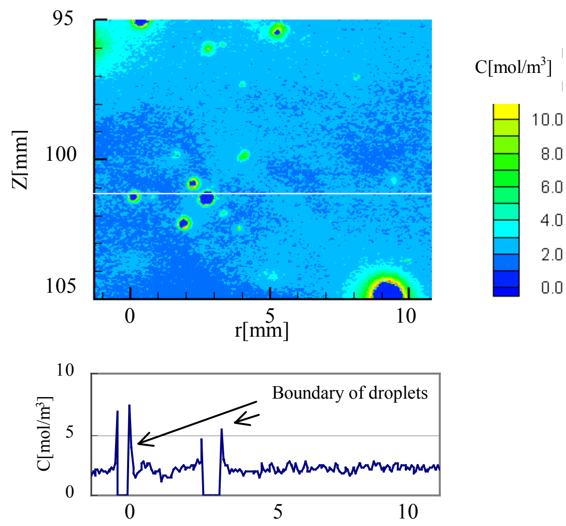


Figure 7. Radial vapor concentration profile at indicated line in the image

4 ILIDS

Simultaneous measurement of size and velocity is carried out by the advanced ILIDS (Maeda *et al*, 2000). The characteristic of this technique lies in three points; (a); the receiving optics, (b); image processing for counting the number of fringes and (c); the calculation of velocity vector.

(a) The compression receiving optics enables us to measure a denser spray without the overlap of the circular fringe images. Figure 8 illustrates the simplified arrangement of the anamorphic optics that consists of the rectangular aperture, circular objective lens, a pair of cylindrical lenses and a CCD camera. A pair of cylindrical lenses was located between the CCD camera and the objective lens in order to generate the out-of-focus images on a focus plane. The roles of the rectangular aperture in front of the objective lens as shown in Figure 8 are (a) to adjust the collecting angle and (b) to enhance the depth of focus.

(b) The numbers of fringes are obtained by Fourier analysis of the spatial frequency information for the fringes. We adopted a fitting method for peak determination with subpixel accuracy in the frequency domain (Kobashi *et al* 1990). This method remarkably reduces the bias error of the calculated frequency to less than 1% for the fundamental frequency. The bias error for absolute diameter can be reduced to less than 0.02.

(c) The velocities v_p of the individual particles are obtained by the displacement ΔS of the interferogram between two images, which is captured by CCD camera with a double-pulsed laser illumination with the time interval Δt. The displacement of the interferogram was estimated by finding the location of the maximum of the cross correlation function of each fringe images, so the velocity is measured for each droplet.

As a result, ILIDS can provide each droplet size and velocity spatially shown in Fig.9.

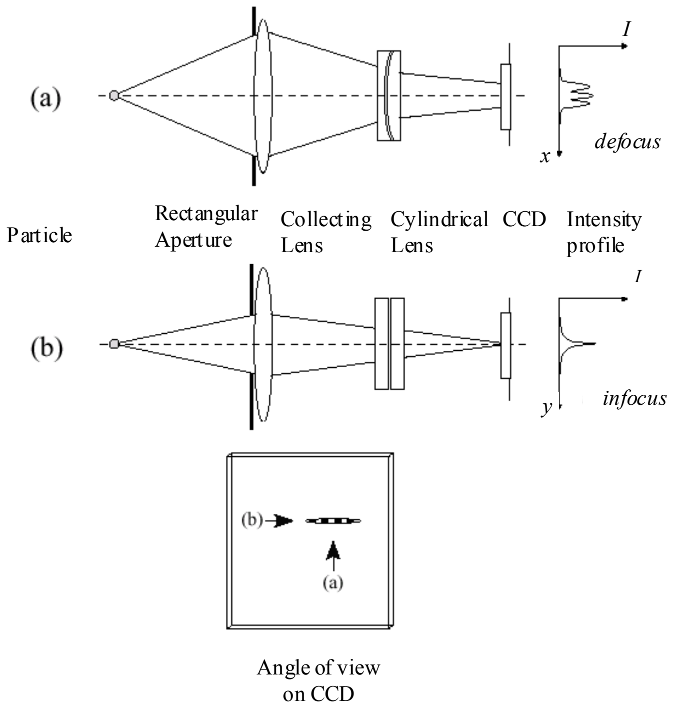


Figure 8. Schematic of the receiving optics by orientation and image

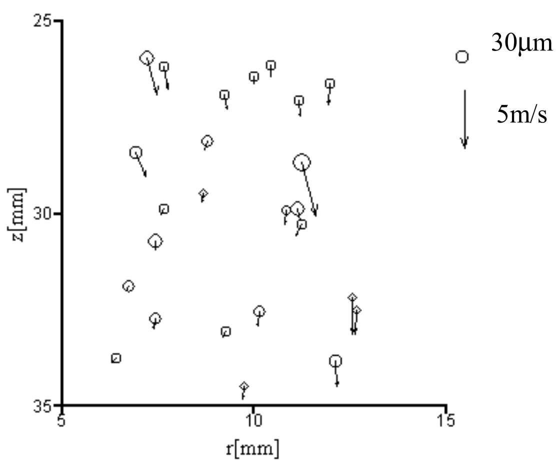


Figure 9. An example of ILIDS result

5 Experimental setup

The experimental setup for the present study is shown in Fig.2. As is described in previous section, we employed Nd:YAG Laser with special optical arrangement (NEW WAVE Research ,50mJ in 532nm for ILIDS, 20mJ in 266nm for LIF) to excite and illuminate the droplets and the vapor. The double-pulse interval was 10μs. Now, circular polarized incident light was applied for better recognition of the fringe and background, and two cylindrical lenses was adopted to make laser sheet with 500μm width. The fluorescence from acetone was captured by high sensitivity CCD camera (HAMAMATSU PHOTONICS C4880-80 14BIT 246×328 pixels) and interference fringed images by reflection and refraction were captured by high resolution CCD camera (KODAK MEGAPLUS ES1.0 /10BIT 1018×1008pixels). Measurement region of LIF was 11×14mm and ILIDS was 10×10mm, so the spatial resolution of LIF was 45μm and ILIDS was 10μm by a pixel. The maximum frame rate of the camera is 1.6Hz for LIF and 30Hz for ILIDS, so the frame rate of this system is 1.6Hz. The scattering angle was 73 deg. and p=0 and p=1 light was almost the same intensity. The collecting angle was 10 deg. which was calculated by the distance from the collecting lens to the center of object plane and the collecting lens effective diameter.

When a spray flew, the top and bottom of the chamber (200×200×250mm) opened. On the other hand, this chamber was completely closed to make the uniform vapor concentration field when we obtained the reference image. Moreover, on the top of the chamber, it had the vent to extract the vapor by the syringe for the measurement of the reference concentration C_{ref}. The spray nozzle (Delavan, type B, 0.5GPH, solid cone) was employed with a pressure of 0.2MPa. The nozzle was connected with the three-dimensional traverser, so the laser, and the chamber and receiving optics could be settled to make the same distribution of non-uniformity.

6 Result and discussion

6.1 Mean Vapor concentration and velocity distribution

When we calculate the mean vapor concentration in a spray, we should note the existence of droplets. In the present method, the droplets are cut off by the threshold, so the vapor concentration information lacks when the droplets exist. Therefore, the averaged vapor concentration by a pixel may have little number of concentration data and little reliability. To solve this problem, we did spatial average in the vapor concentration field. In the prearranged region, 20*20 pixels in the present study, we counted the number of pixels with the vapor concentration data and integrate the vapor concentration, and then average the vapor concentration by the counted number of pixel. Furthermore, we averaged about 100 images to minimize the fluctuation of the laser power, and acquired the mean vapor concentration distribution in a spray. The mean vapor concentration distribution calculated by the present method is shown in Fig.10. The measurement positions were at the axial position z=30, 50, 75mm. The concentration along the spray axis and the concentration gradient to the radial direction are decreasing with increasing the distance from the nozzle, so the diffusion of a spray is confirmed.

Concerning about the droplet properties measured by ILIDS, we verified the distributions of mean axial velocity. We averaged the axial velocity without the consideration of droplet diameter, so the result would be the same with the result measured by convectional PIV/PTV system. The measurement positions were the same with the measurement of the vapor concentration, and the averaged region had 2mm width in each measurement region. The experimental results are shown in Fig.11.The results also show the diffusion of a spray and these are in good agreement with the velocity distribution measured by PIV (Kobayashi *et al*, 2000).

We can confirm that the results of each measurement are in good agreement with previous works, so the simultaneous measurement is possible without any influence to each other.

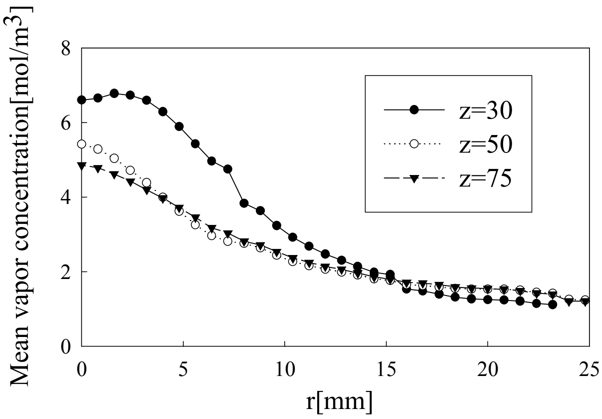


Figure 10. Comparison of mean vapor concentration distributions at the downstream locations z

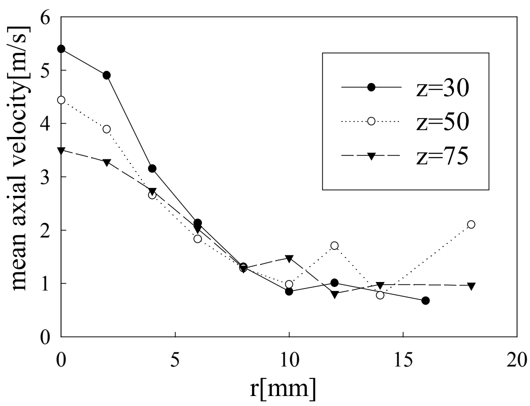
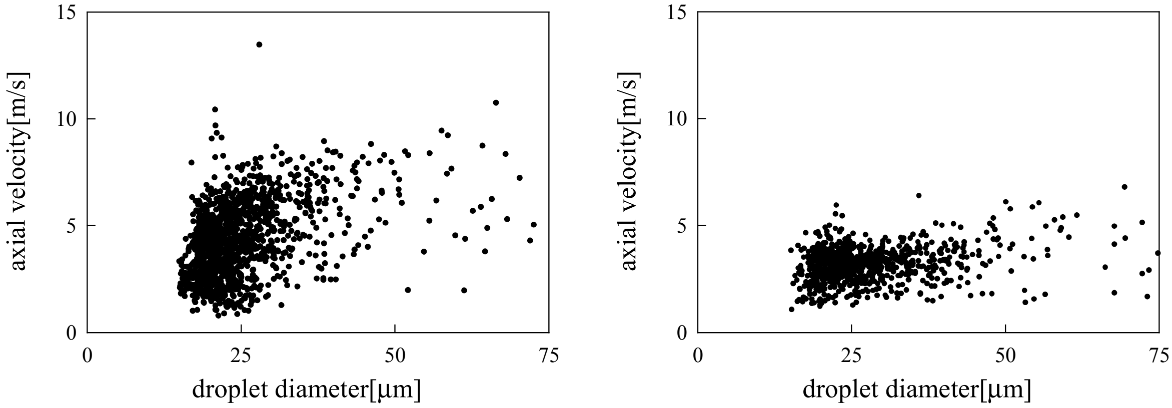


Figure 11. Comparison of mean axial velocity distributions at the downstream locations z

6.2 Distribution of vapor concentration, droplet size and velocity

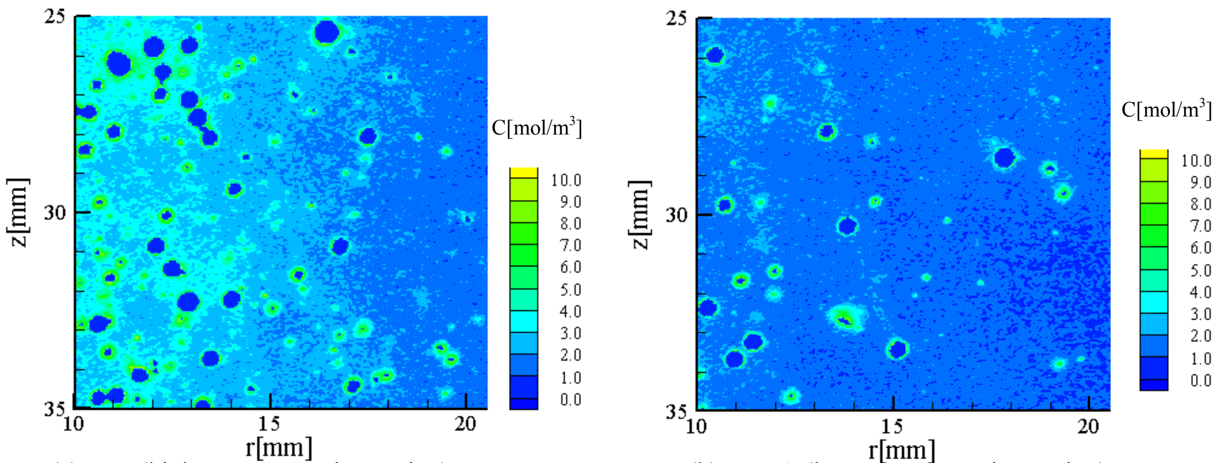
The characteristic of ILIDS is the measurement of droplet size and velocity vector simultaneously and spatially, so we confirm the correlation of droplet diameter with axial velocity under the center line from nozzle as is shown in Fig.12. The correlation diagram at z=30 clearly shows the positive correlation, on the other hand, the positive correlation is going to break down at z=75. This tendency shows that bigger droplets have stronger inertial force at the upstream of a spray, and the smaller droplets gradually converge to the terminal velocity with increasing the distance from the nozzle.

The strongest advantage of the present method is the measurement of the relativity of vapor concentration with droplet properties (size and velocity). Now, we show two instantaneous vapor concentration distributions with the time interval Δt of 6.3 seconds in Fig.13. The time interval of Δt responds to 10 frame intervals in this measurement system. In Fig.13, there are several circular points with blue color, these are droplets cut off by the threshold as is described in previous section. In Fig. 13 (a), we can confirm the cluster with higher vapor concentration and droplet density from r=10 to about r=16, so the edge of a spray will exist around r=16mm, on the other hand, Fig. 13(b) shows lower vapor concentration and droplet density without the edge of a spray. Figure 14 shows spatial droplet velocity vectors distributions separated by the size (b) under 26μm, (c) above 30μ, and 100 images are merged. The relevancy that bigger size droplets flow to the outside of a spray with large velocity and the smaller droplets flow to the inside with smaller velocity clearly appears in Fig.14. These results show that the spray was mixing with the ambient gas actively, and the mixing process is completely unsteady. Therefore, the simultaneous measurement of vapor and droplets is acquired to analyze a spray in details. Figure 15 is the image magnified around r=13,z=34 in Fig.13 (a) and shows simultaneous vapor concentration and droplet size and velocity vector. Though the droplet positions of each measurement are exactly the same, the corresponding of droplets in LIF image and measured by ILIDS is possible, so the present method has the sufficient possibility to make good contribution to the thorough analysis of a spray. The occasion of the positioning error would lie in the accuracy of the position calibration that is caused by the use of two cameras for each measurement.



(a);z=30 (b);z=75

Figure 12.Comparison of correlation between droplet size and droplet axial velocity at the different downstream locations (a);z=30(b);z=75 under the center line from nozzle with 10×10 frame size



(a); $t=t_0$ (higher concentration region) (b);$t=t_0+\Delta t$(lower concentration region)

Figure 13. Comparison with the instantaneous vapor concentration distribution in a spray at z=30,r=15 (Δt=6.3s corresponds to 10 frames)

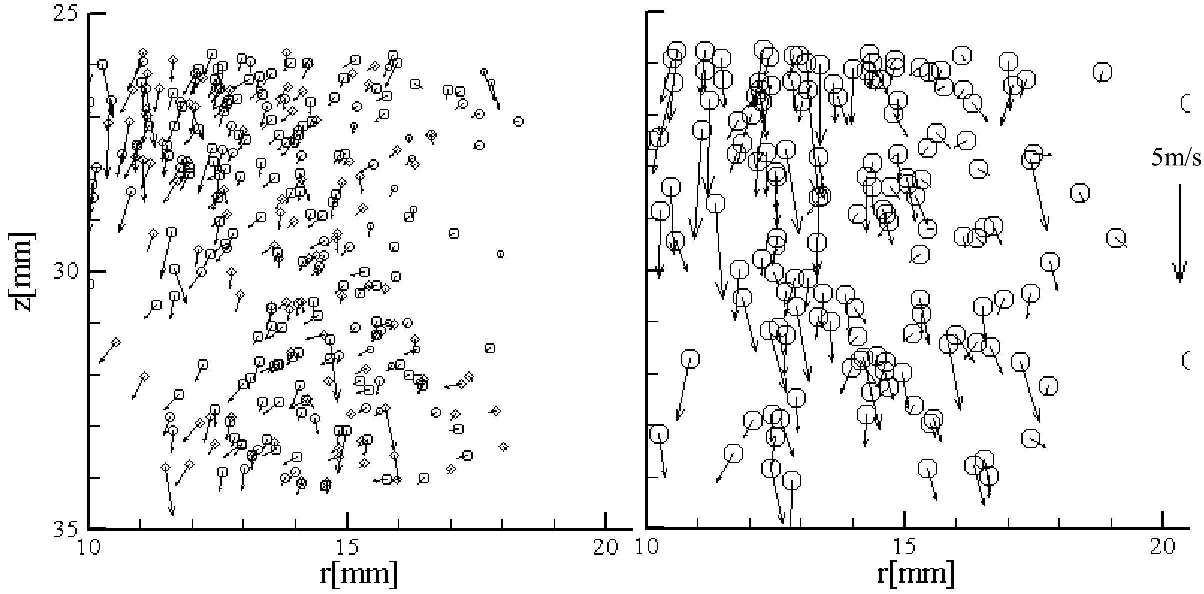


Figure 14. Comparing with the spatial distributions of droplet size and velocity separated by the droplet size (a) under 26µm, (b) above 30µm at the same region of Fig. 13

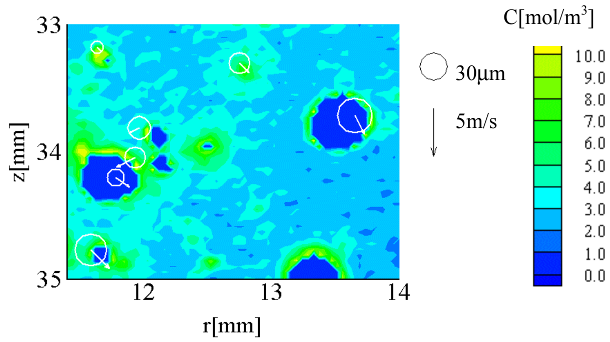


Figure 15. The magnified image of Fig.13 (a) with the information of the droplets by ILIDS

7. Conclusions

The developed measurement technique to combine LIF and ILIDS was carried out by employing the laser sheet that includes two wavelengths to each measurement system and the appropriate optical filters. The fourth harmonic wavelength of Nd:YAG laser excites the acetone as a fluorescence marker and the second harmonic wavelength of the laser illuminates the acetone droplets without excitation. The spectrum peak of acetone differs from the second harmonic wavelength, we can distinguish fluorescence and scattered light with no influence on each measurement.

The experimental results by the present method indicated spatial droplet distribution, size and velocity, and vapor concentration around the droplets by LIF simultaneously. We can correspond droplets in LIF image and that measured by ILIDS even thought there is the slight error of droplet positions captured by each measurement system now. Therefore, the present method has the good possibility to clarify the relevancy of droplets and vapor, such as the evaporation and the mixing of a spray in the internal combustion engines.

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